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Multi Parametric Optimization of WC-Co composites using Desirability Approach

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Abstract

Wire electrical discharge machining (WEDM) plays an important role in the manufacturing industry owing to its ability to generate intricate and complex shapes on workpiece with high dimensional accuracy and surface finish. Tungsten carbide cobalt (WC-Co) metal matrix composites (MMC) commonly finds applications as tool and die materials. Yet due to complex stochastic nature of WEDM process and the involvement of high number of input variables the full potential of the process has not been realized. In this present article material removal rate and surface roughness of the Tungsten carbide-cobalt (WC-Co) composite material subjected to wire electric discharge machining was studied. A 0.25 mm diameter zinc coated copper wire was applied as tool electrode to cut the material. Experiments were designed and conducted using Taguchi's L'32 orthogonal array. Experiments were conducted under different combinations of input variables such as percentage of cobalt in the composite, pulse on time, delay time, wire feed, wire tension, ignition current and di-electric pressure. Three trials were conducted and the average was chosen as the response at that particular experimental condition. Optimization of the multiple process variables were carried out using desirability function analysis. Confirmation experiments were carried out to check the accuracy of the optimized results.

Keywords: WEDM, MRR, Surface roughness, Tungsten carbide-cobalt, Desirability function analysis

1. Introduction

Wire electrical discharge machining (WEDM) has achieved a considerable place in the manufacturing industry owing to its ability to machine conductive and high strength temperature resistive materials [1]. Moreover it is capable of generating intricate and complex shapes on workpiece with high dimensional accuracy and surface finish through low stress on work [2, 3]. During WEDM process a continuously moving conductive wire acts as the electrode. Erosion of material takes place by a series of discrete

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sparks between the electrode and workpiece separated by a thin film of dielectric fluid [4 -6]. The dielectric fluid is used for flushing away the material eroded during the process.

From early 1920s tungsten carbide particles are in industrial existence and cobalt is an element found to be the best additive in binding the particles. Tungsten carbide cobalt (WC-Co) metal matrix composites (MMC) commonly finds applications as tool and die materials [7]. However when high strength WC-Co MMCs are machined by WEDM, chances of electrolytic corrosion is high as the material is prone to electrolyzation [8]. Jun Qu et al. studied surfaces of electric discharge machined WC–Co composites and observed that irregular indents occurred at places of porosity and soft matrix material caused by electrical sparks during the machining process [9]. Due to its extensive industrial applicability it is imperative to study the wire electric discharge machining characteristics of WC-Co composites under varying input parameters for the optimal prediction of process output characteristics [10]. Optimization of WEDM process variables were attempted by several researchers. A mathematical model was developed by Liao et al. [11] and process parameters were optimized by feasible direction method. Regression models [12] and response surface methodology [13, 14] were used to model the cutting speed and surface roughness of WEDM process. Moreover experiments were conducted by Tarng et al [15] to evaluate the dry friction and wear behavior of tungsten carbide cobalt metal matrix composites at varying percentages of cobalt binder phase. Yet due to complex stochastic nature of WEDM process and the involvement of high number of input variables the full potential of the process has not been realized. Moreover studies focusing on optimization of many process variables with more number of experiments for higher degree of accuracy are less. Hence in this study, experiments were designed based on L32 Taguchi's experimental design technique by varying seven variables and then multi-parameter optimized using desirability function approach.

2. Experimental methodology

Tungsten carbide-cobalt metal matrix composites with two different cobalt binder phase percentages (10 % and 20 %) were cut into cross sections of 5 X 5 mm using mm using SODICK AQ 427L WEDM machine tool which has ceramic parts and linear motors to reduce friction and backlash enabling high speed machining. Taguchi's L'32 orthogonal array was used to design the experiments with one two level factor and six four level factors. Three trials were conducted for each experiment planned and the mean of them was taken as the final result. Table 1 shows the parameters and levels used in the experiments.

Surface roughness (Ra) of the wire electric discharge machined tungsten carbide cobalt metal matrix composites was measured using Surf coder SE-1200. Material removal rate was calculated using Eq. (1).

$$MRR = V_c \times B \times H \ (mm^3/min) \tag{1}$$

Where, V_c = machining speed (mm/min),
$B = (2W_g + d)$ (mm)
W_g = wire gap (mm)
D = diameter of electrode wire (mm)
H = thickness of the job (mm)

Table 1. Process parameters and levels

Factors	Parameters	Levels			
		Level 1	Level 2	Level 3	Level 4
A	WC/Co %	10	20	--	--
B	Pulse on time	6	9	12	15
C	Delay Time	10	15	20	25
D	Wire Feed	70	80	90	100
E	Wire Tension	60	80	100	120
F	Ignition Current	8	12	16	20
G	Di-electric Pressure	30	35	40	45

3. Desirability functional analysis (DFA)

Multi parameter optimization using simultaneous response technique is a useful approach for complex processes such as WEDM. In this technique an objective function translates a predicted response into a scale free value desirability ranging between zero and one. Optimal parameter conditions are the factor settings with maximum total desirability. Table 2 shows the experimental plan with average responses for surface roughness and material removal rate.

Table 2. Experimental plan with surface roughness (Ra) and material removal rate (MRR) response

Test No	Process parameters							Response	
	A	B	C	D	E	F	G	Ra	MRR
1	1	1	1	1	1	1	1	2.17	18.33
2	1	1	2	2	2	2	2	2.42	22.12
3	1	1	3	3	3	3	3	2.98	18.99
4	1	1	4	4	4	4	4	2.37	22.12
5	1	2	1	1	2	2	3	2.20	20.68
6	1	2	2	2	1	1	4	2.22	20.68
7	1	2	3	3	4	4	1	2.20	18.52
8	1	2	4	4	3	3	2	2.81	22.12
9	1	3	1	2	3	4	1	2.67	18.88
10	1	3	2	1	4	3	2	2.30	18.41
11	1	3	3	4	1	2	3	2.98	20.44
12	1	3	4	3	2	1	4	2.02	18.17
13	1	4	1	2	4	3	3	2.30	20.17
14	1	4	2	1	3	4	4	2.02	20.87
15	1	4	3	4	2	1	1	2.98	17.65
16	1	4	4	3	1	2	2	2.39	22.12
17	2	1	1	4	1	4	2	2.25	20.99
18	2	1	2	3	2	3	1	2.98	17.25
19	2	1	3	2	3	2	4	2.23	18.12
20	2	1	4	1	4	1	3	2.30	17.49
21	2	2	1	4	2	3	4	2.47	20.68
22	2	2	2	4	2	3	4	2.39	17.23
23	2	2	3	2	4	1	2	2.50	17.95
24	2	2	4	1	3	2	1	2.90	22.12
25	2	3	1	3	3	1	2	2.65	20.39
26	2	3	2	4	4	2	1	2.54	17.68
27	2	3	3	1	1	3	4	2.98	18.92
28	2	3	4	2	2	4	3	2.95	18.52
29	2	4	1	3	4	2	4	2.85	17.24
30	2	4	2	4	3	1	3	2.14	19.19
31	2	4	3	1	2	4	2	2.12	17.82
32	2	4	4	2	1	3	1	2.24	17.76

3.1 Optimization steps for desirability function analysis

Step 1: The individual desirability indexes were calculated for the responses such as material removal rate and surface roughness using desirability functions. For the material removal rate (MRR) higher the better desirability function is used and for surface roughness (Ra), smaller the better function is used. The functions were chosen because MRR should be higher for given optimum settings whereas Ra should be less (in other words the surface should be smooth).

The desirability function of the smaller-the-better can be written as given in Eq. 2 and the desirability function of the larger the better is given in the Eq. 3

$$\mathrm{d_i} = \begin{cases} 1, & y_j \le y_{\min} \\ \left(\dfrac{y_j - y_{\max}}{y_{\min} - y_{\max}}\right)^r, y_{\min} \le y \le y_{\max}, r \ge 0 & r \ge 0 \\ 0, & y_j \ge y_{\max} \end{cases} \tag{2}$$

$$\mathrm{d_i} = \begin{cases} 1, & y_j \le y_{\min} \\ \left(\dfrac{y_j - y_{\min}}{y_{\max} - y_{\min}}\right)^r, y_{\min} \le y_j \le y_{\max}, r \ge 0 & r \ge 0 \\ 0, & y_j \ge y_{\max} \end{cases} \tag{3}$$

'y_{min}' represents the lower tolerance limit of 'y_j', 'y_{max}' represents the upper tolerance limit of 'y_j' and 'r' represents the weight. The 'r' in Eq. 1 indicates the weights and is defined according to the requirement of the user.

Step 2: Desirability indexes of individual responses are converted into composite desirability (d_G) using the following Eq. 4.

$$d_G = \sqrt[w]{\left(d_1^{w1} \times d_2^{w2} \ldots d_i^{wi}\right)} \tag{4}$$

'd_i' is the individual desirability of the property Yi, 'w_i' is the weight of the property 'Y_i' in the composite desirability and 'w' is the sum of the individual weights.

Step 3: The optimal combination of levels for various factors are found. If the composite desirability value is higher, then the product quality is better. Therefore, on the basis of the composite desirability (d_G), the parameter effect and the optimum level for each controllable parameter are estimated.

Step 4: The significant parameters are identified from ANOVA analysis. The calculated total sums of square values are used to measure the relative influence of the parameters.

Step 5: The predicted optimum condition is selected and then the output characteristics are determined and verified for those optimal level of design parameters.

Table 3 displays the evaluated individual and composite desirability for each of the experiments conducted with L'32 orthogonal array. If the composite desirability value is higher it implies that the result of that particular experiment is closer to the ideal value. In addition it is also possible to individually identify the effect of each process variables from the composite desirability values at different levels.

Table 3. Calculated individual desirability and composite desirability

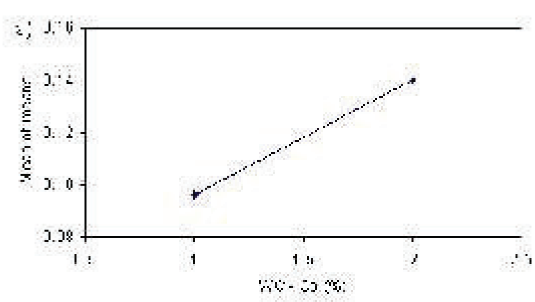
Test No	Individual desirability (di)		Composite Desirability (dG)	Test No	Individual desirability (di)		Composite Desirability (dG)
	Ra	MRR			Ra	MRR	
1	0.14	0.14	0.14	17	0.08	0.19	0.13
2	0.00	0.19	0.00	18	0.84	0.13	0.33
3	0.02	0.08	0.04	19	0.06	0.19	0.11
4	0.10	0.13	0.11	20	0.19	0.04	0.08
5	0.26	0.17	0.21	21	0.04	0.78	0.19
6	0.02	0.14	0.06	22	0.00	0.18	0.03
7	1.00	0.03	0.18	23	0.01	0.18	0.04
8	0.05	0.13	0.08	24	0.03	0.04	0.03
9	0.08	0.10	0.09	25	0.09	0.10	0.09
10	0.04	0.00	0.00	26	0.10	0.12	0.11
11	0.06	0.18	0.10	27	0.04	0.11	0.06
12	0.02	0.04	0.03	28	0.14	1.00	0.38
13	0.04	0.13	0.08	29	0.30	0.12	0.19
14	0.22	0.14	0.17	30	0.87	0.15	0.36
15	0.05	0.62	0.18	31	0.09	0.04	0.06
16	0.06	0.07	0.06	32	0.06	0.05	0.05

Table 4 shows the response mean of average composite function at each level. The mean of means for the entire set of experiments for every parameter is also displayed. The maximum composite desirability value that gives the optimum process parameters and its levels is A2 B4 C1 D4 E2 F4 G3.

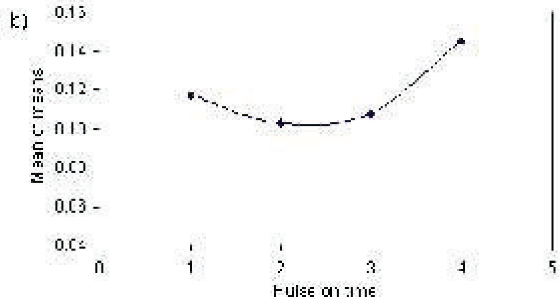
Table 4. Response table for composite desirability

Machining parameters	Average Composite desirability				Max-Min
	1	2	3	4	
A	0.10	0.14			0.04
B	0.12	0.10	0.11	0.14	0.04
C	0.14	0.13	0.10	0.10	0.04
D	0.10	0.10	0.13	0.14	0.05
E	0.09	0.16	0.12	0.10	0.07
F	0.12	0.10	0.10	0.16	0.06
G	0.14	0.06	0.18	0.01	0.16
Total mean of composite desirability = 0.114716					

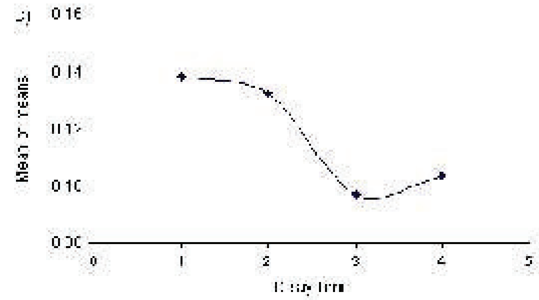
The relative importance between the various parameters at different levels for the multiple performance characteristics in the response graphs of the composite desirability value displayed in Fig 1.



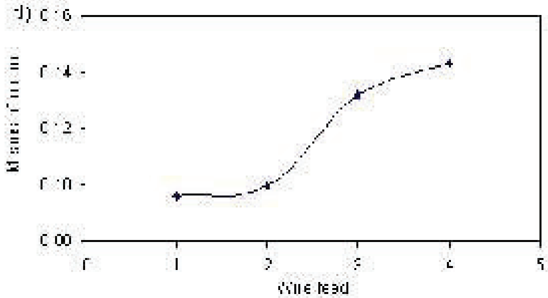
a) Percentage of composite with mean of means



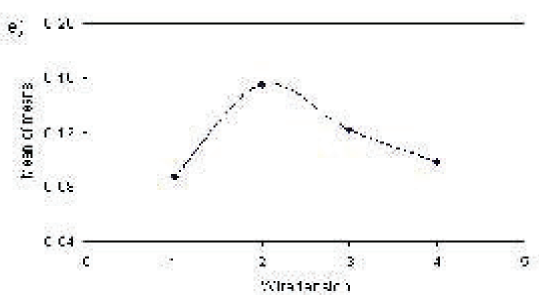
b) Pulse on time with mean of means



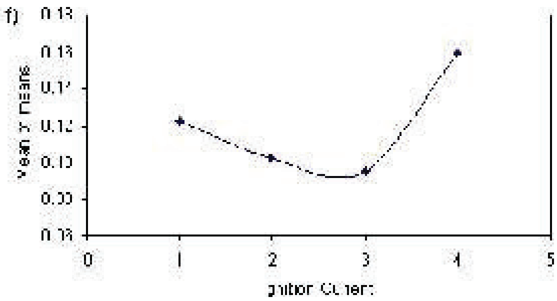
c) Delay time with mean of means



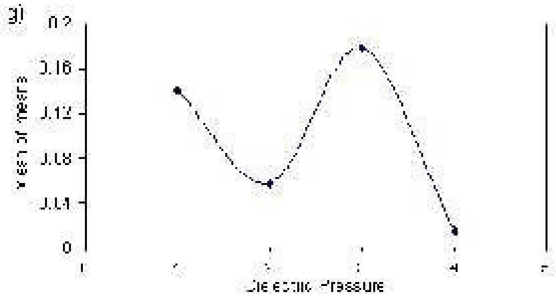
d) Wire feed with mean of means



e) Wire tension with mean of means



f) Ignition current with mean of means



g) Dielectric pressure with mean of means

Fig 1. (a-g) Response graph for composite desirability

4. Analysis of variance

Using ANOVA table the input parameters that significantly affect the output performance characteristics such as Ra and MRR can be found out. This is achieved by categorizing the total variability of the composite desirability value, into contributions by each machining parameter and the error. Table 5 shows the results of ANOVA analysis. Results of analysis of variance for composite desirability value indicate that the delay time is the most significant factor in affecting the multiple performance characteristics.

Table 5. ANOVA table for the composite desirability

Factors	Sum of square ss	Degree of freedom dof	Mean square ms	F calculated	%
A	0.123	3	0.041	4.457	13
B	0.174	3	0.058	0.020	18
C	0.180	3	0.060	0.021	15
D	0.175	3	0.058	0.020	12
E	0.172	3	0.057	0.020	15
F	0.111	3	0.037	0.013	10
G	0.167	3	0.056	0.019	10
Error	0.092	10	0.009		8
Total	0.980	31			100

5. Confirmation Experiments

Confirmation experiments were performed to check the improvement in the output characteristics using the optimal level of input parameters. The estimated composite desirability value ή using the optimum level of the input parameters can be calculated using the Eq. 5.

$$\acute{\eta} = \eta_m + \sum_{i=1}^{q} \left(\overline{\eta}_j - \eta_m \right) \tag{5}$$

'η_m' is the total mean of the composite desirability value, '$\overline{\eta}_j$' is the mean of the composite desirability value at the optimum level and 'q' is the number of input parameters that significantly affects the output performance characteristics. The results of the confirmation experiments are displayed in Table 6. Surface roughness Ra decreased from 4.53 μm to 3.28 μm and the material removal rate MRR improved from 1.33 to 1.18.

Table 6. Result of confirmation experiment

S. No.	Output	Initial machining parameters	Optimal machining parameters	
			Prediction	Experiment
1.	Setting level	A1B4C4D3E1F2G2		A2B4C1D4E2F4G3
2.	Surface roughness (Ra) in µm	2.52	--	1.90
3.	Material removal rate (MRR)	19.52	--	21.24
4.	Composite desirability value	0.06	0.37	0.18
Improvement in composite desirability value = 0.31				

6. Conclusion

- Multi parameter optimization of tungsten carbide cobalt metal matrix composites were done using desirability approach and the following conclusions are drawn.
- For optimal machining conditions the percentage of cobalt binder phase needs to be 20 % within tungsten carbide cobalt metal matrix composites.
- The optimal machining parameters are pulse on time 15 µsec, delay time 10 µsec, wire feed 100 mm/min, wire tension 80 N, ignition current 20 Amps and di-electric pressure 40 Pascals.
- Using the composite desirability analysis, surface roughness values improved from 2.52 µm to 1.90 µm (roughly 23 %) and material removal rate values increased from 19.52 to 21.24 (approximately 8.1%)

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